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### PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53 (c).

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60/430424

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<input type="checkbox"/> Additional Inventors are being named on the _____ separately numbered sheets attached hereto					
TITLE OF THE INVENTION (280 characters max)					
A SIMPLIFIED DECODER FOR A BIT INTERLEAVED COFDM-MIMO SYSTEM					
CORRESPONDENCE ADDRESS					
Direct all correspondence to:					
<input checked="" type="checkbox"/> Customer Number		24737		Place Customer Number Bar Code Label here	
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<input checked="" type="checkbox"/> Firm or Individual Name		Koninklijke Philips Electronics N.V.			
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<input checked="" type="checkbox"/> Drawing(s) Number of Sheets		5	<input type="checkbox"/> Other (specify)		
<input type="checkbox"/> Application Data Sheet. See 37 CFR 1.76					
METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT (check one)					
<input type="checkbox"/> Applicant claims small entity status. See 37 CFR 1.27.					
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<input checked="" type="checkbox"/> No.					
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Respectfully submitted,  
SIGNATURE

Date

12/03/2002

TYPED or PRINTED NAME

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REGISTRATION NO.  
(if appropriate)

48,027

Docket Number:

US020490

TELEPHONE 914 333-9608

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This collection of information is required by 37 CFR 1.51. The information is used by the public to file (and by the PTO to process) a provisional application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 8 hours to complete, including gathering, preparing, and submitting the complete provisional application to the PTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, Washington, D.C., 20231. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Box Provisional Application, Assistant Commissioner for Patents, Washington, D.C. 20231.

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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE  
In re Application of Atty. Docket  
MONISHA GHOSH, ET.AL. US020490

Serial No. Group Art Unit:

Filed: CONCURRENTLY

Title: A SIMPLIFIED DECODER FOR A BIT INTERLEAVED COFDM-MIMO SYSTEM  
Commissioner for Patents Washington, D.C. 20231

APPOINTMENT OF ASSOCIATES

Sir:

The undersigned Attorney of Record hereby revokes all prior appointments (if any) of Associate Attorney(s) or Agent(s) in the above-captioned case and appoints:

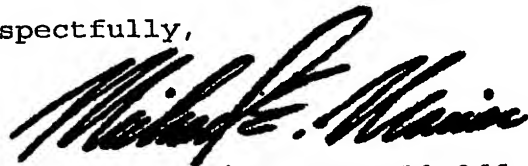
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c/o PHILIPS ELECTRONICS NORTH AMERICA CORPORATION, Intellectual Property and Standards, 580 White Plains Road, Tarrytown, New York 10591, his Associate Attorney(s)/Agent(s) with all the usual powers to prosecute the above-identified application and any division or continuation thereof, to make alterations and amendments therein, and to transact all business in the Patent and Trademark Office connected therewith.

ALL CORRESPONDENCE CONCERNING THIS APPLICATION AND THE LETTERS PATENT WHEN GRANTED SHOULD BE ADDRESSED TO THE UNDERSIGNED ATTORNEY OF RECORD.

Respectfully,



Michael E. Marion, Reg. 32,266  
Attorney of Record

Dated at Tarrytown, New York  
this December 3, 2002.

## IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of

Atty. Docket

MONISHA GHOSH, ET.AL.

US020490

Serial No.

Group Art Unit

Filed: CONCURRENTLY

Ex.

Title: A SIMPLIFIED DECODER FOR A BIT INTERLEAVED COFDM-MIMO SYSTEM

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Washington, D.C. 20231

AUTHORIZATION PURSUANT TO 37 CFR §1.136(a)(3)  
AND TO CHARGE DEPOSIT ACCOUNT

Sir:

The Commissioner is hereby requested and authorized to treat any concurrent or future reply in this application requiring a petition for extension of time for its timely submission, as incorporating a petition for extension of time for the appropriate length of time.

Please charge any additional fees which may now or in the future be required in this application, including extension of time fees, but excluding the issue fee unless explicitly requested to do so, and credit any overpayment, to Deposit Account No. 14-1270.

Respectfully submitted,

By 

Aaron Waxler, Reg. 48,027  
Patent Agent  
(914) 333-9608

## **A SIMPLIFIED DECODER FOR A BIT INTERLEAVED COFDM-MIMO SYSTEM**

### **BACKGROUND OF THE INVENTION**

5

#### **1. Field of the Invention**

The present invention relates to a simplified decoder for a coded orthogonal  
10 frequency division multiplexing-multiple input multiple output (COFDM-MIMO) system.  
More particularly, the present invention relates to a bit interleaved system with maximum  
(ML) likelihood decoding. Most particularly the present invention relates to a 2 by 2  
MIMO system with Zero Forcing (ZF) guided maximum likelihood (ML) decoding that  
doubles the transmission data rate of a single input single output (SISO) IEEE 802.11a  
15 system based on orthogonal frequency division multiplexing (OFDM) technique.

#### **2. Background of the Invention**

MIMO systems have been studied as a promising candidate for the next generation  
of high data rate wireless communication system. Currently, for a single antenna system  
20 (SISO), IEEE 802.11a employing the OFDM modulation technique has a maximum data  
transmission rate of 54 Mbps. There is only one transmission antenna and one receiving  
antenna, i.e., it is a SISO system, and the signal constellation for 802.11a is 64 quadrature  
amplitude modulation (QAM). Transmission data rates in excess of 100Mbps is a goal for  
the next generation wireless communication system.

Given the physical channel characteristics of wireless communication systems, it is almost impossible to increase the data rate with a single antenna system by increasing the order of the constellation of the signal.

One possible approach to achieving a greater than 100Mbps data rate is a 2 by 2 MIMO system based on an IEEE 802.11a SISO system in which the two transmission antennae transmit different data streams that are coded in the same way as an 802.11a system at each antenna. This system can achieve a transmission data rate of 108Mbps with approximately the same signal-to-noise ratio (SNR) as the prior art 54 Mbps IEEE 802.11a SISO system based on OFDM modulation that is illustrated in FIG. 1. FIG. 2 illustrates a prior art 2 by 2 MIMO system that could be used in this way.

Suppose the system of FIG. 2 employs optimal decoding and the wireless channel is defined as  $H = \begin{pmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{pmatrix}$ , where  $h_{ij}$  represents the channel from transmitter antenna  $i$  to receiver antenna  $j$ , i.e.,  $Txi$  to  $Rxj$ . Without losing generality, assume the four channels are Rayleigh fading channels that are independent of one another. Then the received signal in frequency domain on subcarrier  $k$  can be expressed as

$$\begin{pmatrix} r_1 \\ r_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{pmatrix} \begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix} \quad (1)$$

Since each subcarrier is decoded separately, the subscript  $ks$  in equation (1) is omitted.

In optimal maximum likelihood (ML) detection, for each received signal pair,  $r_1$  and  $r_2$ , to determine whether a transmitted bit in these symbols is '1' or '0', it is necessary to find the largest probability

5

$$\max( p(r | b)) \quad (2)$$

where  $r = \begin{pmatrix} r_1 \\ r_2 \end{pmatrix}$  and  $b = \begin{pmatrix} b_{1i} \\ b_{2i} \end{pmatrix}$  are the bits in symbol  $s_1$  and  $s_2$  for which a decision needs to be made. In an add white gaussian noise (AWGN) environment, this is equivalent to finding

10

$$\max_{s_m, s_n} \left( \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{|r_1 - h_{11}s_m - h_{21}s_n|^2}{2\sigma^2}} * \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{|r_2 - h_{21}s_m - h_{22}s_n|^2}{2\sigma^2}} \right) |b_{1i}, b_{2i}) \quad (3)$$

$$= \max_{s_m, s_n} \left( \frac{1}{2\pi\sigma^2} e^{-\frac{|r_1 - h_{11}s_m - h_{21}s_n|^2}{2\sigma^2} - \frac{|r_2 - h_{21}s_m - h_{22}s_n|^2}{2\sigma^2}} \right) |b_{1i}, b_{2i})$$

It is also equivalent to finding

$$\min_{s_m, s_n} (|r_1 - h_{11}s_m - h_{21}s_n|^2 + |r_2 - h_{21}s_m - h_{22}s_n|^2) |b_{1i}, b_{2i}) \quad (4)$$

15

In order to determine the bit metrics for a bit in symbol  $s_1$ , the following equation must be evaluated. For bit  $i$  in symbol  $s_1$  to be '0', it is necessary to evaluate

$$m_{li}^0 = \min_{s_m \in S^0, s_n \in S} (|r_1 - h_{11}s_m - h_{21}s_n|^2 + |r_2 - h_{12}s_m - h_{22}s_n|^2) | b_{li} = 0 \quad (5)$$

Where  $m_{li}^0$  represents the bit metrics for bit  $i$  in received symbol  $s_1$  to be '0'.  $S$  represents for the whole constellation point set, while  $S^0$  represents the subset of the constellation point set such that bit  $b_i = 0$ . For bit  $i$  in symbol  $s_1$  to be '1', it is necessary to evaluate

$$m_{li}^1 = \min_{s_m \in S^1, s_n \in S} (|r_1 - h_{11}s_m - h_{21}s_n|^2 + |r_2 - h_{12}s_m - h_{22}s_n|^2) | b_{li} = 1 \quad (6)$$

where  $S^1$  represents the subset of the constellation point set such that bit  $b_i = 1$ .

Using the same method, it is possible to determine the bit metrics for transmitted symbol  $s_2$ . For bit  $i$  in symbol  $s_2$  to be '0', it is necessary to evaluate

$$m_{2i}^0 = \min_{s_m \in S, s_n \in S^0} (|r_1 - h_{11}s_m - h_{21}s_n|^2 + |r_2 - h_{12}s_m - h_{22}s_n|^2) | b_{2i} = 0 \quad (7)$$

For bit  $i$  in symbol  $s_2$  to be '1', it is necessary to evaluate

$$m_{2i}^1 = \min_{s_m \in S, s_n \in S^1} (|r_1 - h_{11}s_m - h_{21}s_n|^2 + |r_2 - h_{12}s_m - h_{22}s_n|^2) | b_{2i} = 1 \quad (8)$$

Then, the bit metrics pairs  $(m_{li}^0, m_{li}^1)$   $(m_{2i}^0, m_{2i}^1)$  are sent to corresponding deinterleavers and

Viterbi decoders for FEC decoding of each of the data streams.



Simulation results show that using optimal decoding, the proposed 108Mbps MIMO system actually performs 4dB better than the SISO 54Mbps system at a BER of  $10^{-4}$ . However, the computation cost for the optimal decoding is very high. To obtain bit metrics for a bit in signal  $s_1$  to be 0 and 1, it is necessary to evaluate  $64 \times 64$  permutations of the  $s_1$  and  $s_2$  constellation, which cannot be accomplished cost effectively with existing computational capabilities. The computation cost for this 2 by 2 MIMO system decoding is too high to be practical.

#### SUMMARY OF THE INVENTION

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Thus, there is a need for an alternative coding method to reduce the high computation cost when a 2 by 2 MIMO system based on and 54Mbps IEEE 802.11a SISO system is employed for increasing the data transmission rate above 100Mbps.

15 The present invention is a 108Mbps 2 by 2 MIMO system based on a 54Mbps SISO system, as illustrated in FIG. 3, that replaces optimal decoding with a simplified decoding method that has about the same computation cost as the optimal SISO decoder and about 1/64 the computation cost of the optimal MIMO decoder. In the system illustrated in FIG. 3, the separate demapping and deinterleaving module 10, of the prior art system illustrated in  
20 FIG. 1, is replaced by a shared demapping and signal separation unit 34 and the separate deinterleaving units 30 and 31.

The present invention employs a ZF guided maximum likelihood (ML) decoding method. For a SISO single carrier system, since a time-dispersed channel (frequency selective fading channel) brings the channel memory into the system, joint maximum likelihood (ML) equalization and decoding is not realistic because of the high computation  
5 cost. The general practice is to first use minimum-mean-square-error/ zero forcing (MMSE/ZF) as the criteria to equalize the channel. Then the equalized signal is sent to a maximum likelihood (ML) detector for further decoding. However, this is a sub-optimal system.

In a SISO OFDM system, since the system is designed to let each sub-carrier  
10 experience flat fading channel, the real maximum likelihood (ML) equalization and decoding can be implemented with affordable computational cost. Yet in a MIMO OFDM system, because of the large number of permutation evaluations of the constellation set required in the metrics calculation, the computation cost for real maximum likelihood (ML) equalization and decoding is too high to be practical.

15 One way to avoid the large number of permutation computations is to first find the approximate value of the transmitted symbols  $s_1$  and  $s_2$  and then use the maximum likelihood (ML) detection method to find the bit metrics for  $s_1$  while taking  $s_2$  as the value calculated by the ZF method. It is reasonable to make the assumption that when the SNR is high enough, the ZF decision is very close to the optimal maximum likelihood decision.  
20 Thus, the present invention incurs approximately the same computation cost in a MIMO system to get the bit metrics for the transmitted symbols  $s_1$  and  $s_2$  as the SISO system incurs for transmitted symbols  $s$ .

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a prior art 54 Mbps IEEE 802.11a SISO system based on OFDM modulation.

FIG. 2 illustrates a prior art 2 by 2 MIMO system.

FIG. 3 illustrates a 108Mbps 2 by 2 MIMO system based on the 54 Mbps SISO system of FIG. 1, according to a preferred embodiment of the present invention.

FIGs. 4A-C illustrate a Slice-Compare-Selection Operation.

FIG. 5 shows simulation results comparing the 108 Mbps MIMO system of FIG. 3 with the 54 Mbps SISO system of FIG. 1.

## DETAILED DESCRIPTION OF THE INVENTION

The preferred embodiments of the present invention employ a simplified decoding method. The details of the simplified decoding method are described below with reference to the drawings.

The received signal can be written as  $\begin{pmatrix} r_1 \\ r_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{pmatrix} \begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix}$ . According to the ZF criteria, the transmitted signal can be estimated by the demapping and signal separation module 34 as

$$\begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{pmatrix}^{-1} \begin{pmatrix} r_1 \\ r_2 \end{pmatrix} \quad (9)$$

Using the minimum Euclidean distance calculated for the ZF calculated symbol and constellation point, the demapping and signal separation module 34 obtains the estimated transmitted symbol by hard decision. The symbols after the hard decision operation can be represented as  $(\hat{s}_1, \hat{s}_2)$ . The bit metrics for transmitted symbol  $s_1$  are then calculated by the demapping and signal separation module 34 as

$$m_{1i}^0 = \min_{s_m \in S^0} (|r_1 - h_{11}s_m - h_{21}\hat{s}_2|^2 + |r_2 - h_{12}s_m - h_{22}\hat{s}_2|^2) | b_{1i} = 0)$$

$$m_{1i}^1 = \min_{s_m \in S^1} (|r_1 - h_{11}s_m - h_{21}\hat{s}_2|^2 + |r_2 - h_{12}s_m - h_{22}\hat{s}_2|^2) | b_{1i} = 1) \quad (10)$$

and bit metrics for transmitted symbol  $s_2$  can then be calculated as

$$m_{2i}^0 = \min_{s_n \in S^0} (|r_1 - h_{11}\hat{s}_1 - h_{21}s_n|^2 + |r_2 - h_{12}\hat{s}_1 - h_{22}s_n|^2) | b_{2i} = 0)$$

$$m_{2i}^1 = \min_{s_n \in S^1} (|r_1 - h_{11}\hat{s}_1 - h_{21}s_n|^2 + |r_2 - h_{12}\hat{s}_1 - h_{22}s_n|^2) | b_{2i} = 1) \quad (11)$$

where  $S^p$  represents the subset of the constellation points such that bit  $b_i$  is  $p$  where  $p=0$  or  $1$ . Then, the bit metrics pairs  $(m_{1i}^0, m_{1i}^1)$   $(m_{2i}^0, m_{2i}^1)$  are sent to corresponding first and second deinterleavers 30 and 31 and different Viterbi decoders 33 and 34, respectively, for forward error correction (FEC) decoding of each data stream.

In a second preferred embodiment, a further simplified decoding method is provided based on the first preferred embodiment. Unlike the first preferred embodiment in which the demapping and signal separation module 34 uses the MIMO ML criteria to calculate the bit metrics for each bit in the two transmitted symbols after the ZF operation, the SISO ML is used by the demapping and signal separation module 34 to find the constellation points for each bit that satisfy

$$\min_{s \in S^p} \|\tilde{s}_q - s\|^2 \quad (12)$$

where  $q = 1, 2$  and  $p \in \{0, 1\}$ . Two constellation points are defined by the demapping and signal separation module 34 that correspond to the bit metrics calculation of (12) for bit  $i$  of the transmitted symbol  $s_q$  to be  $s_{qi}^p$ . In SISO decoding, bit metrics calculated from (12) are sent to a Viterbi decoder for decoding. In MIMO decoding, equation (12) is only used by the demapping and signal separation module 34 to determine the constellation points that satisfy (12) and use these constellation points in MIMO ML criteria to calculate the bit metrics for each bit that are sent to a Viterbi decoder for decoding. That is, the bit metrics are calculated by the demapping and signal separation module 34 as

$$\begin{aligned} m_{1i}^p &= (\|r_1 - h_{11}s_{1i}^p - h_{21}\hat{s}_2\|^2 + \|r_2 - h_{12}s_{1i}^p - h_{22}\hat{s}_2\|^2) \\ m_{2i}^p &= (\|r_1 - h_{11}\hat{s}_1 - h_{21}s_{2i}^p\|^2 + \|r_2 - h_{12}\hat{s}_1 - h_{22}s_{2i}^p\|^2) \end{aligned} \quad (13)$$

Then, the bit metrics pairs  $(m_{1i}^0, m_{1i}^1)$   $(m_{2i}^0, m_{2i}^1)$  are sent to corresponding first and second deinterleavers 30 and 31 and different Viterbi decoders 33 and 34, respectively, for forward error correction (FEC) decoding of each data stream.

In a hardware implementation, the 12 constellation points for the 6 bits in one transmitted symbol can be obtained by a slice-compare-select operation. An example of quadrature-phase shift keying (QPSK) is illustrated in Fig.4A. If the real part of the received symbol is considered, it is possible to determine that the two constellation points corresponding to bit  $b_0$  are the two points connected by the dashed line in FIG. 4B. The same method can be used to determine the corresponding constellation points for bit  $b_1$  by using the imaginary part of the received symbol, as shown in FIG. 4C. With the slicing method, the actual distance calculation of equation (12) is not needed. In the second preferred embodiment, the permutation in distance searching in the MIMO ML bit metrics calculation can be avoided, which reduces the computation cost of the MIMO ML bit metrics calculation.

Simulation results, shown in FIG. 5, confirm the performance of both embodiments of the present invention. The multipath channel simulated is the exponential Rayleigh fading channel defined in Bob O'Hara, Al Petrick; "The IEEE 802.11 Handbook: A Designer's Companion", December 1999, having a 40ns rms delay spread. The four channels across the two transmission antennae and two receiving antennae are independent of each other, which means there is no correlation between any of the four channels. For each data point of the sign-to-noise-ratio vs. bit-error-rate (SNR vs. BER) curves of FIG. 5, 1 million bits equally distributed in 250 packets was simulated. It is reasonable to assume

that the wireless channel for each antenna element is the same for each packet, while it is different for different packets. In all the simulations, ideal frequency and timing synchronization is assumed.

Simulation results show that although the performance of the first embodiment of the simplified decoding method of the present invention is about 4dB worse than the optimal decoding method at a BER level of  $10^{-4}$ , it is almost the same as the optimal decoding for the SISO system at 54Mbps 43. This result shows that the first embodiment of the present invention comprising a 2 by 2 MIMO system 41 can double the transmission data rate of the SISO system 43 for the same SNR at reasonable computation cost. The second embodiment provides the same improvement for a further reduced computation cost. Therefore, the simulation show that both embodiments of the present invention have about the same BER vs SNR performance, which is almost the same as SISO 54Mbps system 43 and 4dB less than MIMO optimal decoding system 42 at BER level of  $10^{-4}$ . And, the increase in transmission rate by double is obtained for no increase in computation cost in the first embodiment and a reduced computation cost in the second embodiment

Referring to FIG. 4, a 2 by 2 MIMO system 42 based on IEEE 802.11a SISO system according to the present invention can provide a 108Mbps transmission data rate that doubles the data rate of the IEEE 802.11a SISO system within the same range of SNR. Optimal decoding of the MIMO system 42 according to the prior art provides 4dB better BER vs. SNR performance than the SISO 54Mbps system 43 at BER level of  $10^{-4}$  but the high computation cost of the optimal decoding makes such an implementation impractical. The present invention provides two preferred embodiments for ZF guided simplified MIMO

decoding, 40 and 41, having computation costs that are almost the same as that of the optimal decoder for the 54Mbps SISO system 43. Although each of the embodiments for a simplified method, 40 and 41, performs 4dB worse than the optimal decoder for MIMO system 42, each provides almost the same SNR performance as the SISO 54Mbps system  
5 43 at the BER level of  $10^{-4}$ , but at the transmission data rate of 108Mbps

While the examples provided illustrate and describe a preferred embodiment of the present invention, it will be understood by those skilled in the art that various changes and modifications may be made, and equivalents may be substituted for elements thereof without departing from the true scope of the present invention. In addition, many  
10 modifications may be made to adapt the teaching of the present invention to a particular situation without departing from the central scope. Therefore, it is intended that the present invention not be limited to the particular embodiments disclosed as the best mode contemplated for carrying out the present invention, but that the present invention include all embodiments falling within the scope of the appended claims.



We claim:

1. A 2 x 2 wireless local area network, comprising:  
a first and a second single input single output (SISO) system respectively having a  
5 first and second transmitter antenna that transmit a first and second transmitted signal  $s_1$   
and  $s_2$ ;  
a first and second receiver antenna that receive a first and second received signal  $r_1$   
and  $r_2$ ; and  
a demapping and signal separation module that employs zero forcing (ZF) to guide  
10 maximum likelihood (ML) decoding and is connected to said first and second SISO system  
and is adapted to process said first and second received signal,  
wherein a data transmission rate of the 2 x 2 system is greater than 100Mbps at a bit error  
rate of  $10^{-4}$  and a computation cost for decoding on the order of the decoding cost for an  
optimal SISO system.

15

2. The 2 x 2 system of claim 1, wherein the demapping and signal separation  
module employs zero forcing (ZF) of the first and second received signal, respectively,  
which received signals correspond to

20

$$\begin{pmatrix} r_1 \\ r_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{pmatrix} \begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix}$$

and results in the first and second transmitted signal being calculated as

25

$$\begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{pmatrix}^{-1} \begin{pmatrix} r_1 \\ r_2 \end{pmatrix}$$

and finds the minimum Euclidean distance between the ZF calculated symbol and a  
constellation point to estimate by hard decision the first and second transmitted signal as  
first and second estimated signal as  $\begin{pmatrix} \hat{s}_1 \\ \hat{s}_2 \end{pmatrix}$  which are then used to guide the maximum  
likelihood (ML) decoding,

30

wherein,  $h_{ij}$  represents a channel from the  $i^{\text{th}}$  transmitter antenna to the  $j^{\text{th}}$  receiver antenna  
and  $n_i$  are noise signals for  $i,j=1,2$ .

3. The 2 x 2 system of claim 2, wherein respective bit metrics calculated for  
first and second transmitted signal  $s_1$  and  $s_2$  are calculated using  $\begin{pmatrix} \hat{s}_1 \\ \hat{s}_2 \end{pmatrix}$  as follows for  $s_1$

35

$$m_{1i}^0 = \min_{s_m \in S^0} (|r_1 - h_{11}s_m - h_{21}\hat{s}_2|^2 + |r_2 - h_{12}s_m - h_{22}\hat{s}_2|^2 | b_{1i} = 0)$$

$$m_{1i}^1 = \min_{s_m \in S^1} (|r_1 - h_{11}s_m - h_{21}\hat{s}_2|^2 + |r_2 - h_{12}s_m - h_{22}\hat{s}_2|^2) | b_{1i} = 1)$$

and for  $s_2$

5

$$m_{2i}^0 = \min_{s_n \in S^0} (|r_1 - h_{11}\hat{s}_1 - h_{21}s_n|^2 + |r_2 - h_{12}\hat{s}_1 - h_{22}s_n|^2) | b_{2i} = 0)$$

$$m_{2i}^1 = \min_{s_n \in S^1} (|r_1 - h_{11}\hat{s}_1 - h_{21}s_n|^2 + |r_2 - h_{12}\hat{s}_1 - h_{22}s_n|^2) | b_{2i} = 1)$$

and the bit metrics pairs  $(m_{1i}^0, m_{1i}^1)$   $(m_{2i}^0, m_{2i}^1)$  are sent to a respective first and second deinterleaver and a first and second Viterbi decoder for decoding, wherein  $b_{1i}$  and  $b_{2i}$  respectively is a bit in signal  $s_1$  and  $s_2$  for which a decision is being made.

4. The 2x2 system of claim 2, wherein the demapping and signal separation module obtains a first and second constellation point,  $s_{1i}^p$  and  $s_{2i}^p$ , satisfying the minimum Euclidean distance from first and second transmitted signal  $\tilde{s}_1$  and  $\tilde{s}_2$  for bit  $i$

$$\min_{s \in S^p} \| \tilde{s}_q - s \|^2$$

where  $q = 1, 2$  and  $S^p$  represents the subset of a constellation point set for bit  $i$ , the bit for which a decision is being made, such that  $p \in \{0,1\}$ , uses these constellation points as input to a maximum likelihood calculation in the form of a bit metrics calculation for  $p=0,1$

$$m_{1i}^p = (\| r_1 - h_{11}s_{1i}^p - h_{21}\hat{s}_2 \|^2 + \| r_2 - h_{12}s_{1i}^p - h_{22}\hat{s}_2 \|^2)$$

$$m_{2i}^p = (\| r_1 - h_{11}\hat{s}_1 - h_{21}s_{2i}^p \|^2 + \| r_2 - h_{12}\hat{s}_1 - h_{22}s_{2i}^p \|^2)$$

and the bit metrics pairs  $(m_{1i}^0, m_{1i}^1)$   $(m_{2i}^0, m_{2i}^1)$  are sent to a respective first and second deinterleaver and a first and second Viterbi decoder for decoding.

5. The 2x2 system of claim 2, wherein the demapping and signal separation module performs a slice-compare-select operation to determine a first and second constellation point,  $s_{1i}^p$  and  $s_{2i}^p$ , corresponding to the ZF signal which first and second constellation point is used as input to a maximum likelihood calculation in the form of a bit metrics calculation for  $p=0,1$

$$m_{1i}^p = (\| r_1 - h_{11}s_{1i}^p - h_{21}\hat{s}_2 \|^2 + \| r_2 - h_{12}s_{1i}^p - h_{22}\hat{s}_2 \|^2)$$

$$m_{2i}^p = (\| r_1 - h_{11}\hat{s}_1 - h_{21}s_{2i}^p \|^2 + \| r_2 - h_{12}\hat{s}_1 - h_{22}s_{2i}^p \|^2)$$

and the bit metrics pairs  $(m_{1i}^0, m_{1i}^1)$   $(m_{2i}^0, m_{2i}^1)$  are sent to a respective first and second deinterleaver and a first and second Viterbi decoder for decoding.

5

6. The 2 x 2 system of claim 1, wherein said first and second SISO system is based on a 54Mbps IEEE 802.11a SISO orthogonal frequency division multiplexing (OFDM) system.

10

7. A decoder for a 2 x 2 coded orthogonal frequency division multiplexing-multiple input multiple output (COFDM-MIMO) system, comprising:

a demapping and signal separation module to develop a first and second bit metrics pair based on zero forcing guided maximum likelihood (ML) decoding of a first and second received signal  $r_1$  and  $r_2$  that correspond to a first and second transmitted signal  $s_1$  and  $s_2$  respectively transmitted and received by said 2 x 2 COFDM-MIMO system; and

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a first and second deinterleaver and Viterbi decoder adapted to receive said first and second bit metrics pairs, respectively, for forward error correction decoding thereof, wherein said decoder enables a transmission rate that is double the transmission rate of an optimal 54Mbps SISO system to 108Mbps at a decoding computation cost comparable to that of the optimal 54Mbps SISO system.

20

8. The decoder of claim 7, wherein the demapping and signal separation module employs zero forcing (ZF) of the first and second received signal, respectively, which received signals correspond to

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$$\begin{pmatrix} r_1 \\ r_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{pmatrix} \begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix}$$

and results in the first and second transmitted signal being calculated as

30

$$\begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{pmatrix}^{-1} \begin{pmatrix} r_1 \\ r_2 \end{pmatrix}$$

and finds the minimum Euclidean distance between the ZF calculated symbol and a constellation point to estimate by hard decision the first and second transmitted signal as

first and second estimated signal as  $\begin{pmatrix} \hat{s}_1 \\ \hat{s}_2 \end{pmatrix}$  which are then used to guide the maximum

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likelihood (ML) decoding,

wherein,  $h_{ij}$  represents a channel from the  $i^{\text{th}}$  transmitter antenna to the  $j^{\text{th}}$  receiver antenna and  $n_i$  are noise signals for  $i,j=1,2$ .

9. The decoder of claim 8, wherein the demapping and signal separation module (34) calculates respective bit metrics for first and second transmitted signal  $s_1$  and  $s_2$  using  $(\hat{s}_1, \hat{s}_2)$  as follows for  $s_1$

$$m_{1i}^0 = \min_{s_m \in S^0} (|r_1 - h_{11}s_m - h_{21}\hat{s}_2|^2 + |r_2 - h_{12}s_m - h_{22}\hat{s}_2|^2) | b_{1i} = 0)$$

$$m_{1i}^1 = \min_{s_m \in S^1} (|r_1 - h_{11}s_m - h_{21}\hat{s}_2|^2 + |r_2 - h_{12}s_m - h_{22}\hat{s}_2|^2) | b_{1i} = 1)$$

10

and for  $s_2$

$$m_{2i}^0 = \min_{s_n \in S^0} (|r_1 - h_{11}\hat{s}_1 - h_{21}s_n|^2 + |r_2 - h_{12}\hat{s}_1 - h_{22}s_n|^2) | b_{2i} = 0)$$

15

$$m_{2i}^1 = \min_{s_n \in S^1} (|r_1 - h_{11}\hat{s}_1 - h_{21}s_n|^2 + |r_2 - h_{12}\hat{s}_1 - h_{22}s_n|^2) | b_{2i} = 1)$$

wherein  $b_{1i}$  and  $b_{2i}$  respectively is a bit in signal  $s_1$  and  $s_2$  for which a decision is being made.

20

10. The decoder of claim 8, wherein the demapping and signal separation module obtains a first and second constellation point,  $s_{1i}^p$  and  $s_{2i}^p$ , satisfying the minimum Euclidean distance from first and second transmitted signal  $\tilde{s}_1$  and  $\tilde{s}_2$  for bit  $i$

25

$$\min_{s \in S, p} \| \tilde{s}_q - s \|^2$$

and uses these constellation points as input to a maximum likelihood calculation in the form of a bit metrics calculation for  $p=0,1$

$$m_{1i}^p = (\| r_1 - h_{11}s_{1i}^p - h_{21}\hat{s}_2 \|^2 + \| r_2 - h_{12}s_{1i}^p - h_{22}\hat{s}_2 \|^2)$$

$$m_{2i}^p = (\| r_1 - h_{11}\hat{s}_1 - h_{21}s_{2i}^p \|^2 + \| r_2 - h_{12}\hat{s}_1 - h_{22}s_{2i}^p \|^2)$$

30

wherein,  $q = 1, 2$  and  $S_i^p$  represents the subset of a constellation point set for bit  $i$  such that  $p \in \{0,1\}$ , and bit  $i$  is the bit for which a decision is being made.

11. The decoder of claim 8, wherein the demapping and signal separation module performs a slice-compare-select operation to determine a first and second constellation point,  $s_{1i}^p$  and  $s_{2i}^p$ , corresponding to the ZF signal which are then used as input to a maximum likelihood calculation in the form of a bit metrics calculation for  $p=0,1$

$$m_{1i}^p = (\| r_1 - h_{11}s_{1i}^p - h_{21}\hat{s}_2 \|^2 + \| r_2 - h_{12}s_{1i}^p - h_{22}\hat{s}_2 \|^2)$$

$$m_{2i}^p = (\| r_1 - h_{11}\hat{s}_1 - h_{21}s_{2i}^p \|^2 + \| r_2 - h_{12}\hat{s}_1 - h_{22}s_{2i}^p \|^2)$$

10

12. A decoding method for a 2 x 2 coded orthogonal frequency division multiplexing multiple input multiple output system, comprising the steps of:  
transmitting by said 2 x 2 system a first and second transmitted signal;  
receiving by said 2 x 2 system a first and second received signal that correspond to  
15 said first and second transmitted signal;  
developing a first and second bit metrics pair based on zero forcing guided maximum likelihood (ML) decoding of said first and second received signal; and  
deinterleaving and decoding said first and second bit metrics pairs to obtain a first and second decoded signal,  
20 wherein said decoder enables a transmission rate that is double the transmission rate of an optimal 54 Mbps single input single output SISO system to 108Mbps at a decoding computation cost comparable to that of the optimal 54 Mbps SISO system.

13. The decoding method of claim 12, wherein said developing step further comprises the steps of:  
separating the first and second received signal into a first and second separated signal;  
obtaining by hard-decision a first and a second constellation point which is respectively closest to the first and second separated symbol;  
30 with the second constellation point fixed, calculating the first bit metrics pair using ML criteria and the first separated signal; and  
with the first constellation point fixed, calculating the second bit metrics pair using ML criteria.

14. The decoding method of claim 12, wherein said developing step further comprises the steps of:  
separating the first and second received signal into a first and second separated signal;  
obtaining a first and second constellation point which satisfies the minimum  
40 Euclidean distance from the first and second separated signal; and

calculating a first and second bit metrics pair using the first and second constellation point as input to a maximum likelihood calculation.

- 5        15.    The decoding method of claim 12, wherein said developing step further comprises the steps of:
- separating the first and second received signal into a first and second separated signal;
- obtaining a first and second constellation point corresponding to the separated signal by a slice-compare-select operation; and
- 10        calculating a first and second bit metrics pair using the first and second constellation point as input to a maximum likelihood calculation.

## ABSTRACT

Multiple input multiple output (MIMO) systems are candidates for higher data rate wireless communication systems. Currently, for a single input single output (SISO) IEEE 802.11a system can provide a transmission data rate up to 54Mbps. The present invention is a 2 by 2 Multiple In Multiple Out (MIMO) system having a decoding apparatus that increases the data rate to over 100Mbps but at a computation cost about the same as for optimal decoding for a SISO system and 1/64 of the optimal decoding for a 2 by 2 MIMO system. At a bit error rate (BER) of  $10^{-4}$  level, the 2 by 2 MIMO system of the present invention provides double the transmission data rate of the SISO system with approximately the same signal to noise ratio (SNR).

# PRIOR ART

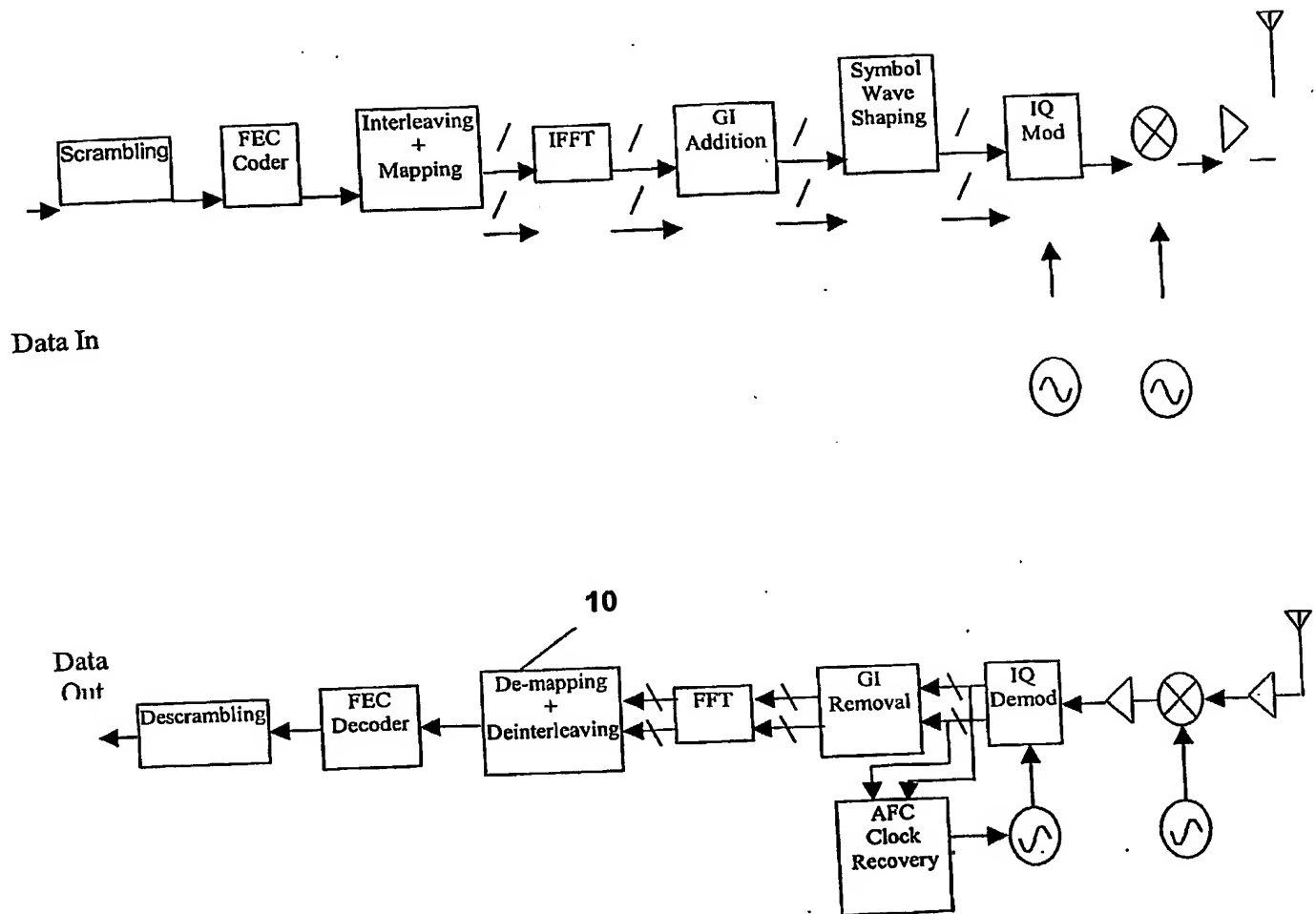
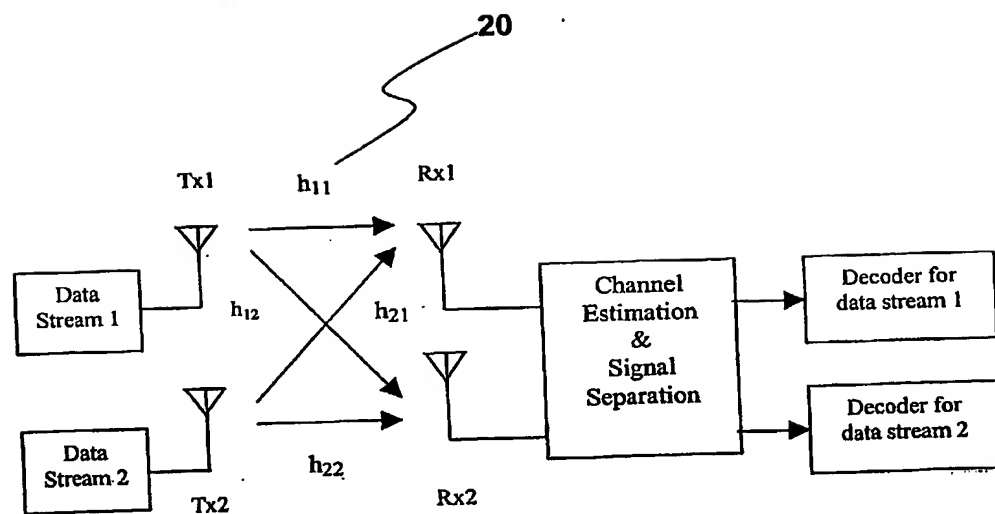
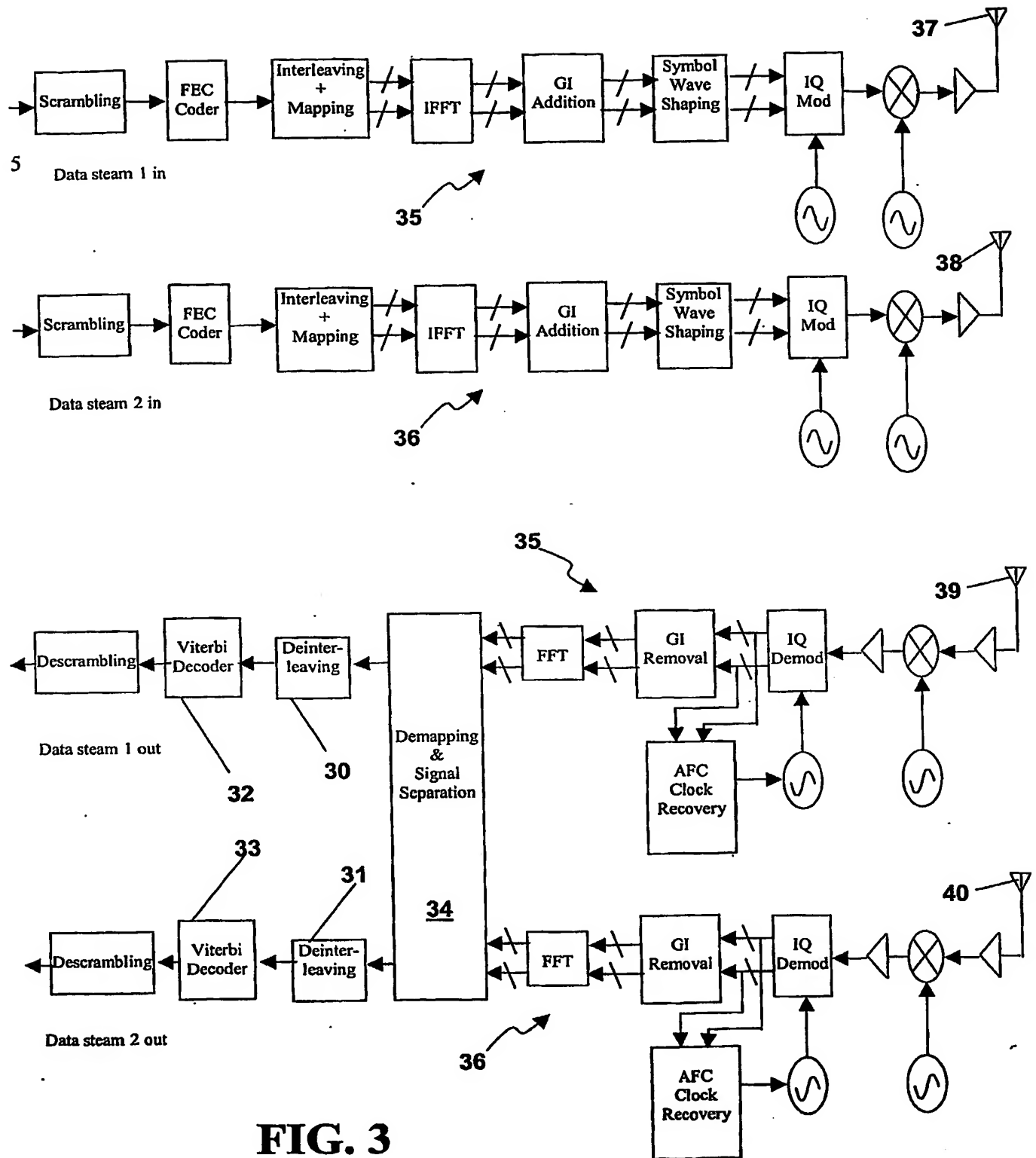


FIG. 1

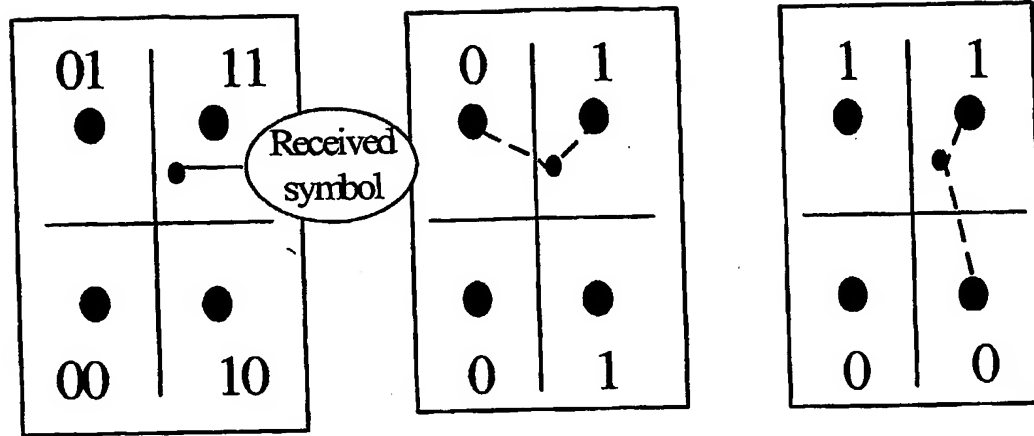
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**FIG. 2****BEST AVAILABLE COPY**



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A) QPSK constellation

B) Bit  $b_0$ C) Bit  $b_1$ 

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FIG.4

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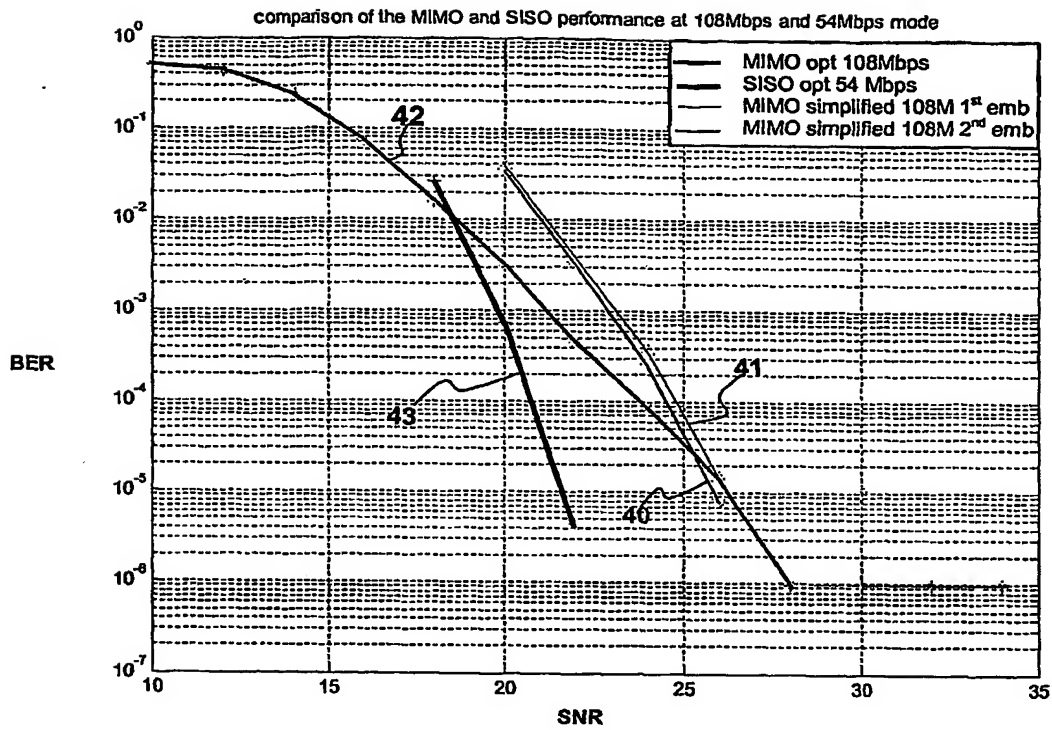


FIG. 5

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